JOURNAL OF MATERIALS PROCESSING TECHNOLOGY 201 (2008) 751–754

journal homepage: www.elsevier.com/locate/jmatprotec

Glass material model for the forming stage of the glass molding process

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ARTICLE INFO

Keywords:
Glass molding process
Elasto-viscoplastic
FE

ABSTRACT

The aim of this research is to obtain an accurate material model for glass that can be used in finite element (FE) analysis of the glass molding process. A thorough understanding of the deformation behavior of the glass specimens was acquired by performing uniaxial compression tests. The elasto-viscoplastic model was utilized for the glass material at the molding temperature to construct the FE model, and a suitable set of parameters for this material model was verified by comparing the simulation results to the experimental data. As a result, the feasibility of the elasto-viscoplastic model for glass at the molding temperature was confirmed; this material model can be used in FE analysis of the prediction and modification of properties of the final lens products.

1. Introduction

In recent years, glass molding technology has been widely used to produce the small scale optical lenses used in 3C products. A feature of this technology is that glasses are heated to a temperature above the glass transition temperature (Tg) or even the yield point (At) and are formed by replication from the same mold in high numbers (Meden-Pielinger, 1983; Taniguchi, 1999; Firestone et al., 2005; Yi et al., 2006). The ability to produce large numbers of replicas and the imprint characteristic make this glass molding technology an ideal choice, more preferable to the conventional glass grinding/polishing technology used to make aspherical lenses.

There are three stages of the glass molding process: heating, molding and annealing. During the heating stage, both molds and glass are heated to the molding temperature, and a fixed displacement is then applied in order to proceed with open/closed die forming in the forming stage. In the subsequent annealing stage, the molds are held in the final position of the forming stage and cooled along with the glass until the mold-releasing temperature is reached; the glass is then separated from the molds.

Glass is a temperature-sensitive material, and both the forming and annealing stages, in which the glass undergoes high temperature variation, will greatly affect the precise shape and dimensions of glass lenses. Consequently, defects in the optical properties of glass lenses will be affected by the deviations in shape and dimension. In addition, the lifetime of the molds used in the forming stage is another critical problem that is encountered in mass production. Therefore, this study focuses on the forming stage of the glass molding process.

It is known that low temperature processes help to lengthen the operating lifetime of the mold material (SCHOTT, in press). In the molding stage, the higher the molding tem-

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0924-0136/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.jmatprotec.2007.11.294

perature, the lower the pressure, and vice versa. The molding temperature currently used by the industry is between 30 °C and 40 °C above At, i.e., the molding temperature is high, and the operating lifetime of the molds is shortened. If the molding temperature is lowered, the pressure increases, which also shortens the operating lifetime of the molds. In order to retain a good operating lifetime for the molds, a compromise between temperature and pressure was made in this study, with the molding temperature set to 30–50 °C above Tg. Uniaxial compression tests were performed at this molding temperature and the stress–strain relationships were observed in the first part of this study. A finite element (FE) model of the uniaxial compression tests was then constructed; analyses were performed and the simulation results were compared to the experimental data. Attempts were made to find an accurate material model for the FE analysis. After the feasibility of the material model was verified, it could then be introduced into the FE analysis of the glass molding process.

2. Material model

Several studies have regarded glass as a viscoelastic material and have focused on its stress relaxation behavior (Scherer, 1986; Rekhson, 1986; Gy et al., 1994; Duffre‘ne et al., 1997; Duffre‘ne and Gy, 1997). Jain et al. (2005) not only focused on the measurement of the viscosity of glass at the molding temperature but also utilized FE analysis for the glass molding process; this study regarded glass as a viscoelastic material (Jain and Yi, 2005; Jain et al., 2006). When discussing the bottle formation of glass at a high temperature, glass is regarded as behaving as a Newtonian fluid, where the viscosity is temperature-dependent, and the material model is rigid-viscoplastic (Hyre, 2002; MSC, 2005). Yi and Jain (2005) also attempted to utilize the rigid-viscoplastic model in FE analysis of the glass molding process.

In order to fully understand the material behavior of glass in the forming stage, and to develop an accurate material model which not only can be used in FE analysis of the glass molding process, but also in the microstructure imprinting procedure, the elastic properties of glass should be considered. In this research, the elasto-viscoplastic model (Cristescu and Suliciu, 1982) was introduced to investigate the deformed behavior of glass in the molding stage. This model is described by

$$\begin{cases} \sigma = E\varepsilon, & \text{if } \sigma < \sigma_Y \\ \sigma = 3\eta(T)\dot{\varepsilon}, & \text{if } \sigma \geq \sigma_Y \end{cases} \tag{1}$$

where σ is the stress, $\eta(T)$ the temperature (T) dependent viscosity, and $\dot{\varepsilon}$ is the strain rate. This function shows that the material behaves as a linear elastic material before the flow stress (σ_Y) is reached, and as a strain rate-dependent viscoplastic material after the flow stress is reached. Although the viscosity varies with temperature, it will be regarded as constant during this analysis because the temperature is fixed in the molding stage.

3. Experiments

In order to find a material property of the glass that can be used in FE analysis of the glass molding process, uniaxial compression tests on the glass material S-FPL52 (with Tg equal to 445 °C), fabricated by the OHARA company, were performed at the chosen molding temperature (475 °C). The strain rate was held at $0.00667\,\mathrm{s}^{-1}$, and the experiments were conducted without lubricant. Cylindrical specimens of 10 mm in diameter and 6 mm in height were used. The FE model of the uniaxial compression test at the molding temperature was then built using a commercial FE program, MSC.MARC, as shown in Fig. 1. Both the upper and lower molds were set as rigid bodies, and the glass specimen was set as an elasto-viscoplastic material. The parameters of the material model were adjusted using the trial and error method to achieve the best-fitting simulation results in comparison with the experimental data.

The friction model, used to model the interfacial friction conditions between the glass and molds, is described by

$$\tau = mk_m \tag{2}$$

where τ is the frictional stress of the interface, m the shear factor ($0 < m < 1$), and k_m is the shear yield stress of the glass near the interface. A shear friction factor of 1.0 was used, which assumes complete sticking between the glass and molds (Yi and Jain, 2005).

4. Results and discussion

The comparison results of the experiment and simulation are shown in Figs. 2 and 3. A set of parameters for the material model was obtained from these trial and error attempts such that Young’s modulus was equal to 1300 MPa and viscosity was equal to 10^{10} P (1000 MPa s). The simulation results fitted with the experimental data quite well, and show that this set of parameters is feasible under the condition of a strain rate of $0.00667\,\mathrm{s}^{-1}$.

To verify whether or not the elasto-viscoplastic model consisting of this set of parameters is feasible for FE analysis under different strain rates, further comparisons between simulation results and experimental data were made. Uniaxial compression tests with strain rates of $0.00833\,\mathrm{s}^{-1}$ and

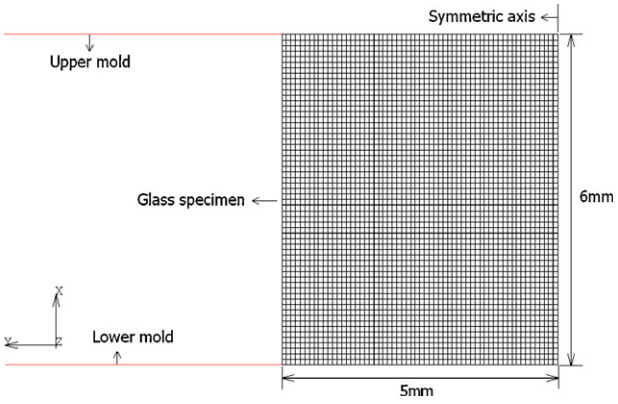

Fig. 1 – 2D axisymmetric model of a glass specimen.

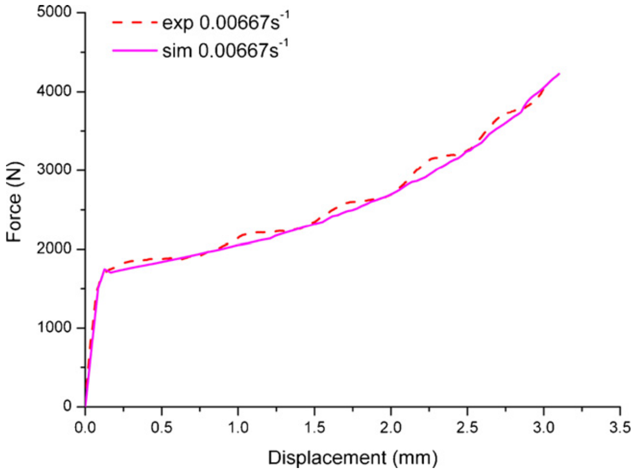

Fig. 2 – Comparison of force–displacement curves between experimental and simulation results at a strain rate of 0.00667 s^{-1}.

0.01 s^{-1} were performed, and the flow stresses under each strain rate were found to be 24.9 MPa and 30 MPa, respectively. Comparisons of the simulation results and experimental data are shown in Figs. 4 and 5, from which it can be seen that the simulation results using the previously obtained material parameters fitted to the experimental data quite well. Therefore, the elasto-viscoplastic model is feasible for describing the deformation behavior of the glass in the molding stage with different strain rates.

The final shape of the glass specimen after compression is shown in Fig. 6 and the simulation result is shown in Fig. 7. Due to the limitations of the apparatus, some parallel deviations exist between the upper and the lower molds, which may cause the nonuniform deformation of the glass specimen; temperature control of the environment and both molds also have some discrepancies. For glass material, a small difference in temperature or pressure could change the final shape of the product. It can be seen from these two figures that

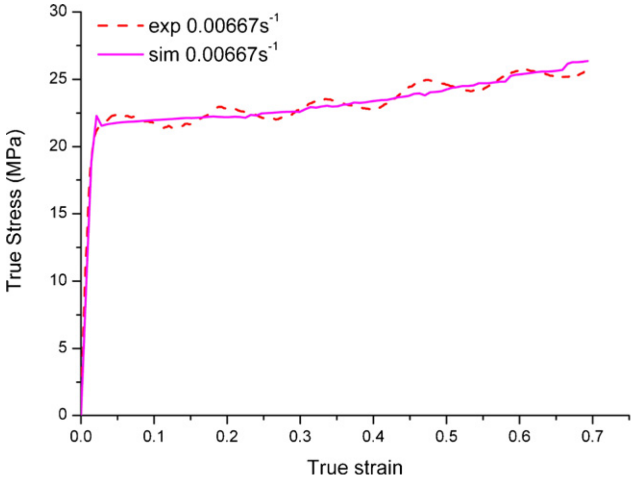

Fig. 3 – Comparison of stress–strain curves between experimental and simulation results at a strain rate of 0.00667 s^{-1}.

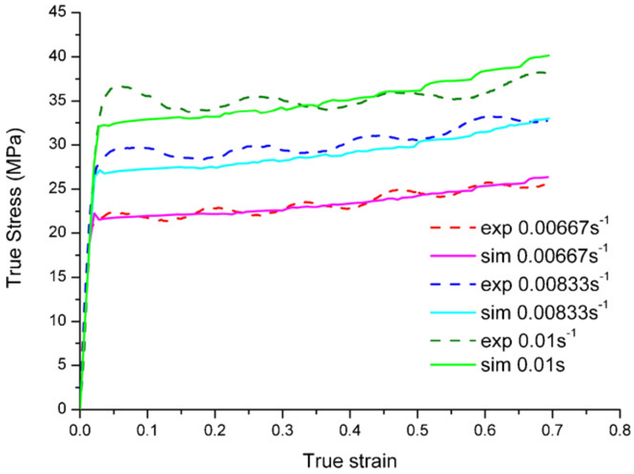

Fig. 4 – Comparison of force–displacement curves between experimental and simulation results at strain rates of 0.00667 s^{-1}, 0.00833 s^{-1} and 0.01 s^{-1}.

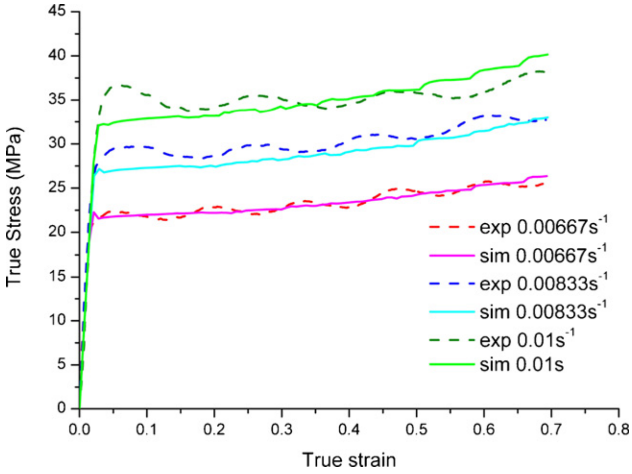

Fig. 5 – Comparison of stress–strain curves between experimental and simulation results at strain rates of 0.00667 s^{-1}, 0.00833 s^{-1} and 0.01 s^{-1}.

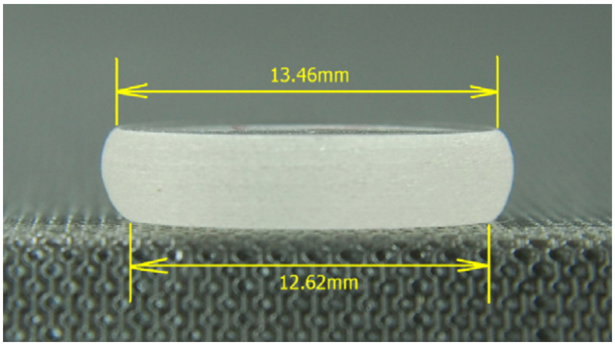

Fig. 6 – Final shape of the glass specimen.

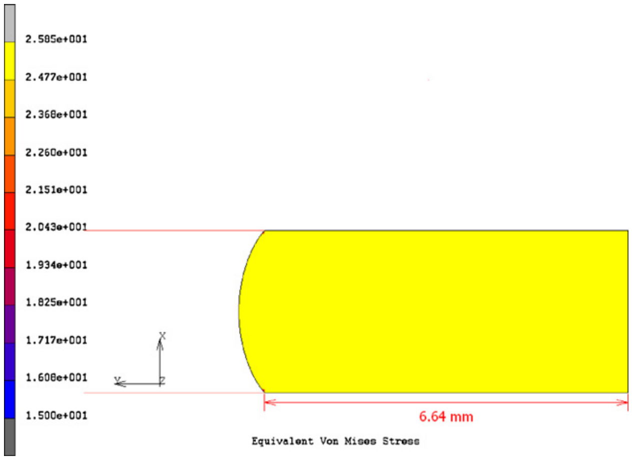

Fig. 7 – Simulation results of the final shape of the glass specimen.

the glass ends were not deformed as evenly as was shown in the simulation results. Nevertheless, this study can still provide a reference for a material model that can be used in FE analysis of glass molding. More precise investigations will be performed when the precision of the apparatus is improved.

5. Conclusion

Research on the deformation behavior of glass at a specific molding temperature (30 °C above Tg) was performed in this work, and the feasibility of the elasto-viscoplastic model for glass material in the molding stage was verified by comparing the simulation results to the experimental data. Some conclusions from this work can be made as follows:

(1) The elasto-viscoplastic model can be introduced into FE analysis of the glass molding process during the molding stage.
(2) The investigations performed in this work are within the molding stage. However, annealing is also a key stage in the glass molding process and will also affect the precision of the final product shape. In order to perform FE analysis more precisely, and to reduce the residual stress of the products to improve the optical properties, the stress relaxation characteristic of the viscoelastic property of the glass material should be considered in the annealing stage. Also, thermal properties in the annealing stage such as heat conduction between the molds and glass, convection between the environment and the glass and molds, and change in the thermal expansion coefficient should be considered thoroughly.
(3) Molds were assumed to be rigid bodies in this work, but in the glass molding process, elastic recovery of the molds will affect the prediction of the final product shape. Therefore, consideration of the elastic property of the molds should be included in the FE analysis in order to pre-compensate for the molds in advance and to predict the final shape of the glass lens more precisely.

Acknowledgements

The authors would like to thank the National Science Council of Taiwan, ROC for the grant NSC 95-2221-E-009-176, under which the investigation was undertaken. The authors would also like to thank the National Center for High-Performance Computing for its facility support.

REFERENCES

Cristescu, N., Suliciu, I., 1982. Viscoplasticity. Martinus Nijhoff.
Duffre‘ne, L., Gy, R., 1997. Viscoelastic constants of a soda-lime-silica glass. J. Non-Cryst. Solids 211, 30–38.
Duffre‘ne, L., Gy, R., Burlet, H., Piques, R., 1997. Viscoelastic behavior of a soda-lime-silica glass: inadequacy of the KWW function. J. Non-Cryst. Solids 215, 208–217.
Firestone, G.C., Jain, A., Yi, A.Y., 2005. Precision laboratory apparatus for high temperature compression molding of glass lenses. Rev. Sci. Instrum. 76.
Gy, R., Duffre‘ne, L., Labrot, M., 1994. New insights into the viscoelasticity of glass. J. Non-Cryst. Solids 175, 103–117.
Hyre, M., 2002. Numerical modeling of glass forming and conditioning. J. Am. Ceram. Soc. 85, 1047–1056.
Jain, A., Yi, A.Y., 2005. Numerical modeling of viscoelastic stress relaxation during glass lens forming process. J. Am. Ceram. Soc. 88, 530–535.
Jain, A., Firestone, G.C., Yi, A.Y., 2005. Viscosity measurement by cylindrical compression for numerical modeling of precision lens molding process. J. Am. Ceram. Soc. 88, 2409–2414.
Jain, A., Yi, A.Y., Xie, X., Sooryakumar, R., 2006. Finite element modeling of stress relaxation in glass lens moulding using measured temperature-dependent elastic modulus and viscosity data of glass. Model. Simul. Mater. Sci. Eng. 14, 465–477.
Meden-Pielinger, G.A.A., Van de Heuvel, J.H.P., 1983. Precision pressed optical components made of glass and glass suitable modeling, US Patent 4,391,915.
MSC, 2005. MSC. Marc User’s Guide. MSC Software.
Rekhson, S., 1986. In: Uhlmann, D.R., Kreidl, N.J. (Eds.), Glass Science and Technology. Academic Press Inc., Florida, USA.
Scherer, G.W., 1986. Relaxation in Glass and Composites. Wiley, New York.
SCHOTT Technical Information, Optical glass for precision molding, SCHOTT, in press.
Y. Taniguchi, 1999. Mold for molding optical element, US Patent 5,855,641.
Yi, A.Y., Jain, A., 2005. Compression molding of aspherical glass lenses–a combined experimental and numerical analysis. J. Am. Ceram. Soc. 88, 579–586.
Yi, A.Y., Huang, C., Klocke, F., Brecher, C., Pongs, G., Winterschladen, M., Demmer, A., Lange, S., Bergs, T., Merz, M., Niehaus, F., 2006. Development of a compression molding process for three-dimensional tailored free-form glass optics. Appl. Optics 45, 6511–6518.